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ARCHITECTURAL ACOUSTICS

BY

PAUL R. HEYL

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ABSTRACT

The fundamental principles governing the construction of an acoustically successful auditorium are no longer new, but are not yet generally understood by those engaged in such work. In this circular these principles are stated and an example is worked out showing their practical application to the planning of a new auditorium or to the curative treatment of one that has proved to be unsatisfactory.

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I. HISTORICAL ORIGIN

The scientific study of architectural acoustics is a thing of comparatively recent years. In 1895 Harvard University had just completed the Fogg Art Museum, containing an auditorium which proved almost unusable. The corporation of the university appealed to the scientific staff of the faculty for advice and assistance in the matter, and Prof. W. C. Sabine undertook the study of the case. Two years were spent in the investigation of the questions involved, in the course of which experiments were made in a number of existing and satisfactory auditoriums. As a result, certain fundamental but previously unrecognized principles became clear, which later enabled Professor Sabine to predetermine the acoustic design of the new Boston Symphony Hall (1).¹

These investigations of Sabine were the pioneer scientific work in the subject. So completely and carefully were they carried out that subsequent workers, until very recently, have for the most part merely enlarged our knowledge of the acoustic properties of the various materials commonly used in building construction

II. USUAL DEFECTS OF AUDITORIUMS

The usual defects of auditoriums are three—echo, dead spots, and reverberation. In the usual sense of the term, echo means a definite or articulate repetition of a sound after an interval at least equal to the total duration of the sound that is being repeated, while reverberation means a confused or inarticulate prolongation of the sound.

¹ The figures given in parentheses here and throughout the text relate to the reference numbers in the bibliography given at the end of this paper.

Echo is always a bad feature in a hall; reverberation, on the other hand, is desirable up to a certain point; only in excess is it an evil. Of the two, echo is the more difficult to remove; prevention by foresight in construction, aided by expert advice, if necessary, is the best plan.

1. ECHO

Echo arises by regular reflection of sound from smooth walls, ceilings, or proscenium arches just as a mirror may reflect a beam of light without scattering it. If, however, the surface of the mirror be roughened the reflected light will be diffused in all directions; and if the walls and ceilings of a room be similarly irregular (on a sufficiently large scale) the reflected sound will be scattered, broken up, and its definite or articulate character destroyed. In this case we have what is called reverberation.

The lapse of time before an echo is heard is due to the fact that the reflected sound has traveled a longer path than the sound which comes directly from the source. This difference of path may be such as to cause much mischief. If it amounts to 50 feet or more, the reflected sound of a spoken syllable or note of music may arrive at the ear at the same moment as a later syllable or note which has traveled by the direct path, and so cause confusion.

Generally speaking, auditoriums are less likely to exhibit troublesome echo when their outlines are rectangular. An instructive example of the trouble that may be caused by curved walls is cited by Watson (4) in the case of the auditorium at the University of Illinois, with an approximately circular floor plan and a hemispherical dome. The best that could be done in the way of aftercorrection of the acoustics of the room was only partly satisfactory. Watson regards the complete cure of such a room as hopeless without "surgical treatment"; that is, straightening the walls.

Smooth, hard-finished walls, such as the usual plastered type, are excellent regular reflectors of sound and are consequently likely to produce echo. It becomes of importance, therefore, to break up such surfaces so as to produce irregular distribution of the reflected sound. This is usually done by coffering in the case of ceilings. Examples of this may be seen in many theaters of modern construction. The ceiling, and in some cases, the proscenium arch, are broken up into depressions about 4 feet square, containing a succession of steps totaling a depth of perhaps 8 or 10 inches. An irregular surface of this character breaks up the reflected sound and distributes it in such a way as to minimize echo, and, in fact, to convert it into reverberation. The dimensions which should be assigned to such coffering are not a matter of taste or accident. If the wave length of the incident sound is very large compared to the size of the irregularities it encounters there will be little dispersive effect produced; and, if very small, the smooth spaces inside the coffering may act as regular reflectors. The size mentioned (4 feet in diameter) is a compromise between the average wave length of the male and the female voice.

2. DEAD SPOTS AND SOUND FOCI

Dead spots and sound foci occur as a consequence of echo-producing conditions. Sound travels through the air as a wave of alternate compression and rarefaction, and if a reflected sound wave is retarded

by the proper amount it may happen that the compression of the directly transmitted sound and the rarefaction of the reflected sound arrive at the ear at the same time, neutralizing each other's effect and producing a diminution in intensity. If the reflected sound is retarded a little more it may happen that two compressions coincide, producing an unusually loud sound. The most usual cause of such sound foci, however, is an excessively curved wall or ceiling which concentrates the sound to a focus.

Since dead spots and sound foci arise from the same cause as echo their removal may be brought about by the same treatment. Some care and experience is necessary in order to locate the particular portion of the room which is responsible for the production of a dead spot. Often this can be found only by a cut-and-try experiment, as it is not possible to predict the path of reflected sound with the same accuracy as in the case of light. The reflecting portion once found must be treated in such a way as to decrease its power of regular reflection.

Sabine mentions a case of a theater, the ceiling of which contained a flat oval panel, to which such trouble was traced. In this case an irregular canopy, oval in plan and slightly larger than the panel, was hung just below it with good effect.

Balconies may require special consideration, especially if low and deep. As a rule, this type of balcony should be avoided, as the sound intensity is sure to be diminished at the rear under the balcony, and may be so low that hearing will be difficult.

3. REVERBERATION

A sound produced in a room is reflected back and forth from walls, floor, and ceiling, a portion being absorbed at each reflection until its intensity is so reduced that it becomes inaudible. Owing to the high speed of sound there may be many such reflections in the course of a single second in a room of ordinary size; and the greater the dimensions of the hall the more prolonged will be the reverberation.

If the walls and ceiling of the room be covered with some highly sound-absorbent material, a few reflections may suffice to destroy the sound. Such a room is acoustically "dead" and undesirable. A little reverberation is necessary to satisfy our established tastes and auditory habit, and the desired amount of reverberation is found empirically to increase with the size of the auditorium.

It is customary, since the pioneer work of Sabine, to define the "reverberation time" of a room (perhaps somewhat arbitrarily and artificially) as the time taken for a sound of specified intensity to die away to inaudibility. This standard intensity is a sound somewhat difficult of reproduction. Fortunately, its use is not necessary in ordinary practice, for in most cases the "reverberation time" can be calculated with sufficient accuracy. The method of making this calculation will be explained later.

Excessive reverberation is an evil because it prolongs unduly each syllable or note of music, causing it to interfere with the next. The ideal conditions for intelligibility of sound are two—each syllable should die away before the next arrives, which in ordinary speech may be, perhaps, one-tenth of a second; and the sound must always be loud enough to be heard.

The first of these conditions can always be secured by providing enough sound-absorbing material in the room. For a small auditorium which can easily be filled by the speaker's voice, this is the most important consideration. For a very large room it may be that the amount of absorption dictated by the first condition is so great that the speaker can not be heard in the back of the room. Since the intensity of the human voice can not be much increased it is necessary to compromise between these two conditions and to permit longer reverberation in larger rooms.

In the case of theaters used for sound pictures this compromise is not necessary, as the acoustic output of the loudspeaker is by no means as limited as that of the voice. For such auditoriums there may be employed to advantage a somewhat shorter reverberation time than is desirable for rooms of the same size used for speaking or musical performances.

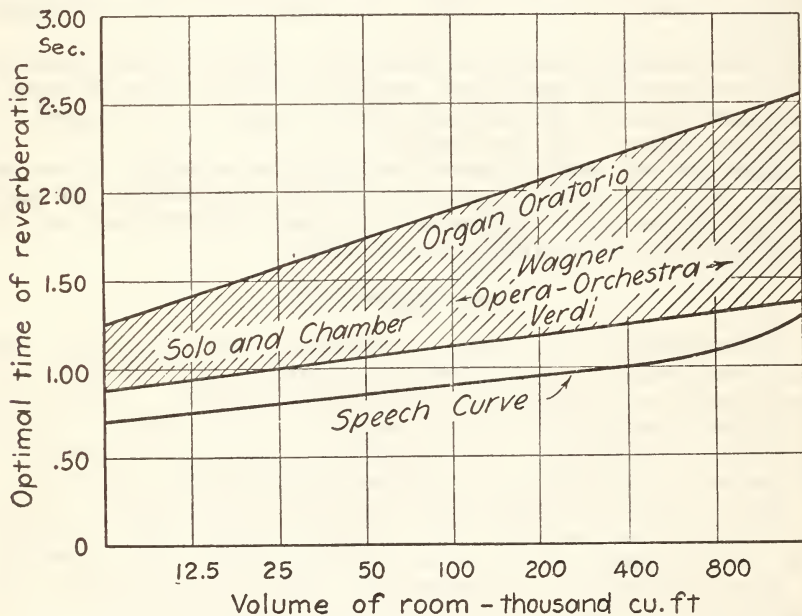


FIGURE 1.—Acceptable limits of standard reverberation time

Broadcasting studios may be equipped with variable absorption, consisting of smooth plaster walls covered with heavy curtains which may be pushed back exposing the wall when more reverberation is desired.

Experience with a number of existing auditoriums of acceptable acoustic quality makes possible the formulation of a table or a diagram in which the acceptable limits of the standard reverberation time are expressed for rooms of different volume, used for speaking or musical performances. Such a diagram, reproduced from an article by Knudson (2), is given in Figure 1. The reverberation time as recommended in this figure is that which should obtain when all the seats are filled.

The limits given in this figure are not to be regarded as rigid. Auditoriums are known which exceed these limits in either direction by several tenths of a second and yet are of fairly satisfactory quality.

And, as mentioned above, large auditoriums used for sound pictures may advantageously be designed for a figure somewhat less than the minimum here suggested.

III. CALCULATION OF THE REVERBERATION TIME

As a result of the investigations of Professor Sabine and later workers (3) the reverberation time of a room may be expressed by a formula. Let

t = reverberation time in seconds.

V = volume of room in cubic feet.

s = total area of absorbing surfaces in square feet.

a = average coefficient of absorption of these surfaces.

$A = as$ = total absorption of room.

Then, according to Eyring (3), the following relation holds:

$$t = \frac{0.05V}{-s \log_e (1-a)} \quad (1)$$

Sabine's formula is simpler, but less accurate. It is:

$$t = \frac{0.05V}{A} \quad (2)$$

Sabine's formula is sufficiently accurate for most rooms, but where the absorption is excessive and the reverberation time very short Eyring's formula must be used.

Different materials differ considerably in their absorbing powers for sound. The most complete absorber known is an open window. It is theoretically possible that a small amount of sound may be sent back by diffraction from the edges of the window, but this quantity is so small that it is permissible to say that an open window is a perfect absorber. A good absorber of sound may absorb, perhaps, half as much sound as an equal area of open window. In other words, if it may be said that an open window absorbs (or transmits) all the sounds that falls upon it, its coefficient of absorption is unity, while that of the material above mentioned would be 0.50.

In like manner, every substance may be said to have its own absorption coefficient. This constant was measured by Sabine for a number of common materials, and later workers have extended the list.

Table 1 gives the absorption coefficient for several substances. Strictly speaking, these coefficients will vary somewhat with the frequency of the incident sound, and in Table 1 the values given are for a frequency of 512 (Watson) (4).

TABLE 1.—*Sound-absorption coefficients*

Concrete.....	0. 015
Glass, single thickness.....	. 03
Marble.....	. 01
Open window.....	1. 00
Plaster.....	. 03
Stage opening (depending on furnishing).....	0. 25-. 40
Ventilators (50 per cent open space).....	. 50
Wood, varnished.....	. 03

Absorption coefficients for a variety of materials have been measured at the Bureau of Standards, and the results, at frequencies ranging from 128 to 4,096 cycles per second, are available upon request.

Sound-absorbing materials are frequently changed by the manufacturers, and a printed list is consequently soon out of date.

In Table 2 there are given values of the total absorption of individual objects for a frequency of 512 cycles per second. The unit of absorption in which these values are expressed is approximately equal to that of 1 square foot of open window.

TABLE 2.—*Total absorption by individual objects*

Audience.....	per person..	4. 0
Church pews.....	per seat..	. 4
House plants.....	per cubic foot..	. 003
Seats, upholstered, depending on material and lining.....	per seat..	1. 0-4. 5
Wood seats, for auditoriums.....	do....	. 25

As an example of the use of these coefficients let us take an auditorium of 100,000 cubic feet capacity, including the stage opening. There is a wooden floor of 4,550 square feet, a plastered ceiling with the same area, 5,320 square feet of plastered walls, a stage opening of 600 square feet, and 500 plain wooden seats. The coefficients for plaster, wood, and glass being the same to the accuracy requisite for this calculation, no special allowance is necessary for closed doors and windows.

The calculation of the total absorption of the empty room is made as follows, the computations being carried to the nearest integer:

Wood floor.....	$4,550 \times 0.03 = 137$
Plaster ceiling.....	$4,550 \times .03 = 137$
Plaster walls.....	$5,320 \times .03 = 160$
Stage opening (no furniture, bare walls).....	$600 \times .25 = 150$
Wooden seats.....	$500 \times .25 = 125$

Total absorption of empty room..... 709

For the absorption of the audience we must add $500 \times 4 = 2,000$ and subtract the absorption of 500 seats at 0.25, giving a net addition of 1,875 absorption units, and bringing the total absorption of the room with full audience up to 2,584. The reverberation time, by Sabine's formula, is then:

$$\frac{0.05 \times 100,000}{2,584} = 1.9 \text{ seconds}$$

which will be seen from Figure 1 to lie at the upper limit for organ and oratorio music, and to be much too great for a few instruments or a speaker. As the absorption of an auditorium is usually not adjustable to the class of performance to be given, a compromise is necessary, and in this case the mean of the upper and lower curves, about 1.4 seconds, will be a suitable value. This would require a total absorption of

$$A = \frac{0.05 V}{t} = \frac{5,000}{1.4} = 3,570 \text{ absorption units.}$$

Since the untreated room with full audience has 2,584 absorption units, there must be added by acoustic treatment 986 units.

The choice of an absorbing material is a question of price and convenience, and sometimes of the space available for acoustic treatment. It should be noted that it is not necessarily the case that materials of the highest coefficient are the most advantageous. Where there is space enough to apply the requisite quantity, a material of low coefficient will give better results than one of higher

absorption, due to the more uniform distribution of material. We will suppose that a material of coefficient 0.25 has been adopted.

Assuming plenty of space, our problem is to replace a certain area of wood or ordinary plaster, both of coefficient 0.03, by a material of coefficient 0.25 so as to obtain 986 additional units of absorption. The net coefficient of the acoustic material will be 0.22, and the area necessary will be

$$\frac{986}{0.22} = 4,482 \text{ square feet}$$

an area which can be contained entirely in the ceiling. In case the ceiling area should not be sufficient, the upper portion of the walls may be treated also. It is not advisable to apply acoustic treatment where it is likely to be damaged by persons passing.

In the above example it will be noticed that all of the added absorption was placed in the auditorium and none on the stage. Experiments conducted by Watson (5) indicate that both speakers and musicians prefer reflecting surfaces about them to intensify the sound while the listeners prefer absorbent material in their neighborhood.

It is generally considered that the reverberation time is independent of the positions of the absorbing material and of the source of sound. In general, this statement is true, but there are some important exceptions. For instance, if the absorbing material is placed back under a balcony or in some other place where the sound intensity is low, the absorbing material will not be as effective as if it were placed where the intensity is greater.

There are also cases where between large parallel nonabsorbent surfaces the sound may be reflected back and forth for a longer time than is to be expected from Sabine's formula. The sound in this case does not resemble ordinary reverberation but may be described as a "flutter," and is heard only when the listener is between the parallel surfaces. Exceptions of this kind are rare, but must occasionally be dealt with.

IV. PLANNING AN AUDITORIUM

In planning an auditorium we must consider three factors—shape, size, and interior finish.

As stated in discussing echo, the design of an auditorium should avoid curved walls or ceilings. An attempt to introduce such features for their artistic effect is almost certain to be detrimental to the acoustic quality of the room. Auditoriums of a rectangular shape have been the most uniformly satisfactory.

Prior to Sabine's work there was current an idea that there should be a certain ratio existing in the dimensions of the room; just what ratio no one seemed to know certainly. Sabine quotes several different recommendations. Modern opinion regards such a ratio as immaterial unless, of course, it be carried to an absurd extreme, such as a very long and narrow room.

The question of size must be determined principally by the purpose for which the room is to be used and not by considerations of space available or seating capacity desired. True, modern amplifying practice makes it possible to use a very large auditorium for speaking, but the present discussion is limited to the consideration of natural features and characteristics. The alteration of quality and the noise introduced by amplifiers are such that they will require much improve-

ment before they will be acceptable for the rendition of anything in which artistic quality is a prime requisite, and for this purpose unassisted auditoriums will for a long time, perhaps always, be the rule.

Generally speaking, a theater must be moderate in size, while an auditorium for musical numbers, such as orchestral or choral performances, may be much larger. Such performances usually include several vocal solo numbers and this rather limits the size of the room.

The absorption of the audience, as may be seen from the example worked out in Section III, is usually a large part of the total absorption of the room. Almost any room will have passable acoustic properties with a capacity audience, but with half the seats empty conditions may be much worse. By the use of upholstered seats the absorption of the room may be rendered more nearly independent of the audience.

It has been found by Watson (5) that in the distribution of the absorbing material the best results are obtained if the material is placed entirely in that portion of the auditorium occupied by the audience, while the wall and ceiling around the stage are left untreated.

Experience with existing auditoriums leads to an empirical rule connecting the volume of the room with the maximum number of orchestral instruments suitable. This rule is expressed in Table 3. No distinction is here made between wind and string instruments, which are supposed to be present in balanced quantity.

In case the orchestra is reinforced by the organ, due allowance must be made. The new music room at the Library of Congress is a case in point. Its volume is about 100,000 cubic feet. At the opening concert there was present an orchestra of 26 pieces, which, with the organ, produced an excessive reverberation perceptibly spoiling the effect of sudden pauses after a loud chord. The indicated limit for this room is, perhaps, 12 or 15 pieces with the organ.

As to interior finish, this should be planned with both echo and reverberation in mind. A liberal use of coffering on ceiling and sloping upper walls should effectually prevent echo from this source, and the interior finish should be calculated to give a reverberation time as indicated by the average range in Figure 1, using panels of absorbing material in such quantity as may be necessary to reduce the reverberation time to a suitable value. Such materials, of several kinds, are now available commercially.

TABLE 3

Volume of room (in cubic feet)	Number of instruments
50,000	10
100,000	20
200,000	30
500,000	60
800,000	90

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